SIMULATIONS OF IMPLODING SOLID LINER MELTING AND VAPORIZATION VS LINER THICKNESS, AND EVIDENCE FOR "MELT WAVES"

J. H. Degnan, G. F. Kiuttu, J. D. Letterio, N. F. Roderick, E. L. Ruden

Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, USA

Abstract

The Air Force Research Laboratory Directed Energy Directorate (AFRL/DE) has, over the last several years, conducted experiments on the magnetic pressure driven implosion of various metal shells (solid liners). More recently, AFRL/DE has reported on experiments that successfully imploded cylindrical aluminum liners suitable for compressing field reversed configurations (FRC's) to magnetized target fusion (MTF) conditions (1). We have recently done Mach2 (2) MHD simulations of the resistive heating of such imploding liners as a function of their thickness. This was to gain insight on diffusion time effects that conceivably could lead to melt waves for thicker liners, driven with higher currents. For example, scaling the thickness of a liner for successful experiment parameters with the implosion discharge energy might be expected to preserve the timing of liner liquification (or loss of material strength). However, diffusion time effects can complicate this. Our simulations indicate such effects, sometimes referred to as melt waves, for increasing the discharge energy and liner thickness a factor of 4, with the same 10 microsecond current risetime, relative to experimentally successful implosion parameters.

I. DESCRIPTION OF SIMULATIONS

The calculations reported here are for 6061-T6 Aluminum liners with height 30 cm, initial outer radius 5.0 cm, and initial inner radii of 5.0 - 0.1 = 4.9 cm for a low energy liner, and 5.0 - 0.413 = 4.587 cm for a high energy liner. The circuit parameters for driving the low energy liner are 1300 microfarads capacitance, 80 kilovolts initial charge, 11 megamps peak current with ~ 10 microsecond risetime, 44 nanohenries initial inductance, and a resistance consisting of a 1 milliohm constant resistance plus a safety fuse. This corresponds closely to the experimentally successful cases reported in (1). For the hypothetical high energy liner, the initial charge voltage is 160 kilovolts, with all other circuit parameters unchanged, resulting in a calculated current peak of 22 megamps, with the same ~ 10 microsecond risetime.

The calculations to date used up to 64 radial zones for the 0.1 cm thick liner, and 258 radial zones for the 0.413 cm thick liner. The number of axial zones was only 8 for these calculations, so they were essentially 1D-MHD. The nonlinear diffusion problem was treated with the SESAME Equation of State Model (3), using the Desjarlais et al resistivity/conductivity model (4), and the Steinberg et al elastic-plastic strength model (5). These calculations were done in Lagrangian mode. Simpler calculations with Mach2 were done with constant diffusivity (6), which confirmed close agreement with the analytic treatment described by Knoepfel (7).

II. RESULTS

The currents vs time for the two cases are shown in Figs. 1 and 2. The inner and outer radii of the liner is shown for both liner cases in Figs. 3 and 4. Due to the approximate incompressibility of the liner until late in the implosion, and, for the outer portion of the liner, until vaporization ensues, the liner thickness increases during the implosion in such a way that constant volume is maintained. The strength parameter vs computational cell was monitored in order to tell what parts of the liner had been heated to change from elastic – plastic to liquid – vapor phase. In this fashion, the fraction of the

Report Documentation Page

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2003	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Simulations Of Imploding Solid Liner Melting And Vaporization Vs Liner Thickness, And Evidence For Melt Waves	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB, NM, USA	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License, The original document contains color images.

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	**SAR**	**4**	
unclassified	**unclassified**	**unclassified**			

liner which has melted vs time was calculated. This fraction (of liner thickness melted, where melt is defined as having lost strength) vs time is shown for the two cases in Figs. 5 and 6. The reduction in the fraction at late times is believed to be due to recompression. That is, some of the melted liner becomes vaporized, but still sufficiently conducting for magnetic pressure to have a compression effect. The melt layer thickness vs time is shown in Figs. 7 and 8.

In both cases, the liner thickness, or cross section, was chosen to avoid melting or vaporization until stagnation. Due to the finite rate of diffusion of magnetic field into the liner, the outer portion is heated more than the inner portion. This causes some of the outer portion to heat to melting, or loss of mechanical strength, prior to the rest of the liner. It can be seen in Figs. 5-8 that this effect is more pronounced for thicker, higher current imploding liners, with the same ratio of current squared to liner cross section. The onset of mechanical strength loss is at ~ 5 microseconds after start of current rise for the 4.13 mm thick, 22 megamp liner vs ~ 17 microseconds for the 1 mm thick, 11 megamp liner. In both cases, much of the liner retains its mechanical strength till stagnation of the inner surface on the axis of symmetry. However, approximately twice the fraction of the thicker liner loses its strength. This earlier onset and higher fraction of melting for the thicker, higher current liners is expected to cause earlier onset and more extreme instability growth. This must be considered in scaling imploding solid liners to higher currents and energies.

Walt Atchison and colleagues have done computational work relevant to this (8), and have pointed out that there are cases where significant melt does not result in rapid instability growth, and other cases where it seems to.

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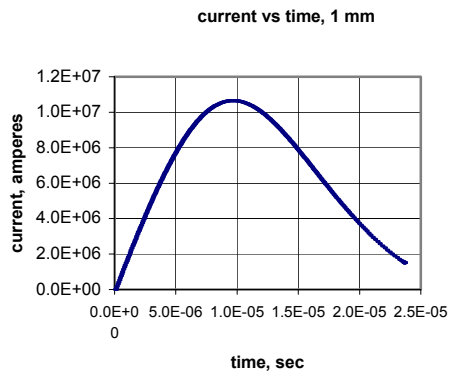
current vs time, 1 mm

Fig.1 Calculated current vs time for initially 1 mm thick Al liner, driven by 1300 microfarad, 44 nanohenry, 80 KV discharge.
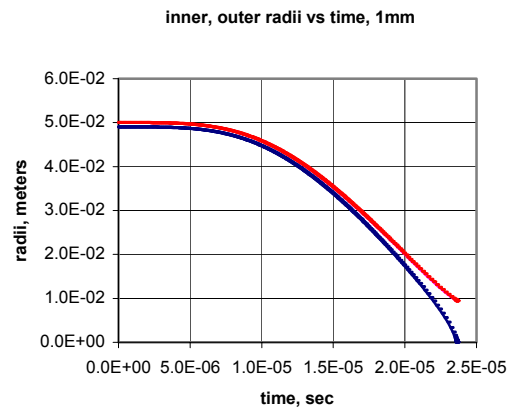
inner, outer radii vs time, 1mm

Fig. 3 Calculated inner and outer radius vs time for initially 1 mm thick Al liner driven by 1300 microfarad, 44 nanohenry, 160 KV discharge.
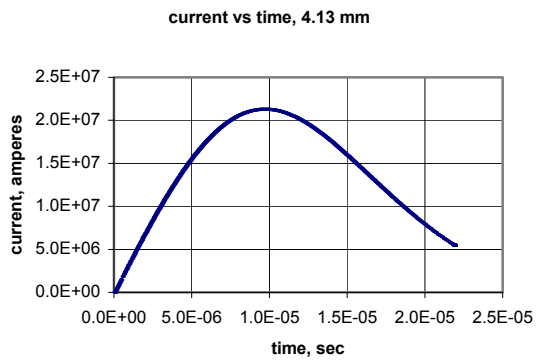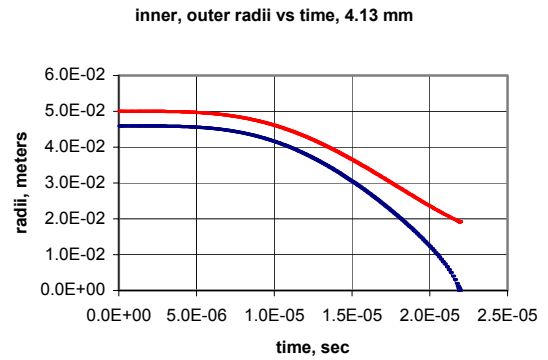
current vs time, 4.13 mm

Fig. 2 Calculated current vs time for initially 4.13 mm thick Al liner, driven by 1300 microfarad, 44 nanohenry, 80 KV discharge.

inner, outer radii vs time, 4.13 mm

Fig. 4 Calculated inner and outer radius vs time for initially 1 mm thick Al liner driven by 1300 microfarad, 44 nanohenry, 160 KV discharge.

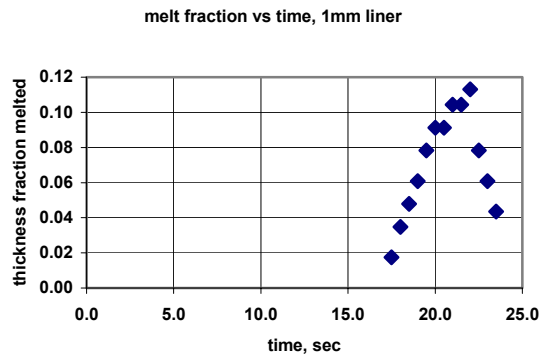**melt fraction vs time, 1mm liner**

Fig. 5 Calculated fraction (vs time) of thickness of liner that has zero mechanical strength (melt layer), for initially 1 mm thick, 5 cm outer radius liner driven by 1300 microfarad, 44 nanohenry, 80 KV discharge.

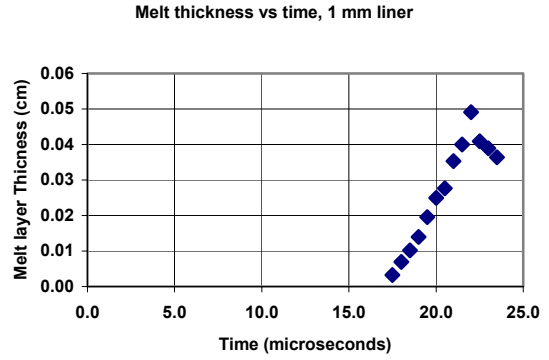**Melt thickness vs time, 1 mm liner**

Fig. 7 Calculated thickness of liner that has zero mechanical strength (melt layer), for initially 1 mm thick, 5 cm outer radius liner driven by 1300 microfarad, 44 nanohenry, 80 KV discharge.

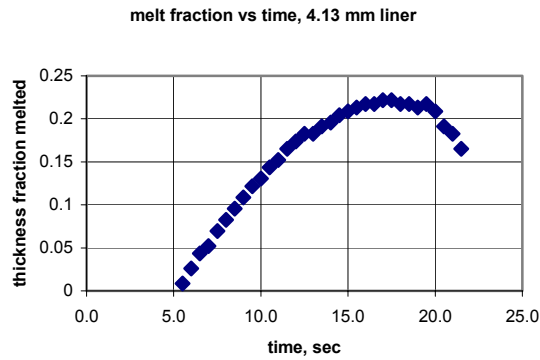**melt fraction vs time, 4.13 mm liner**

Fig. 6 Calculated fraction (vs time) of thickness of liner that has zero mechanical strength (melt layer), for initially 4.13 mm thick, 5 cm outer radius liner driven by 1300 microfarad, 44 nanohenry, 160 KV discharge.
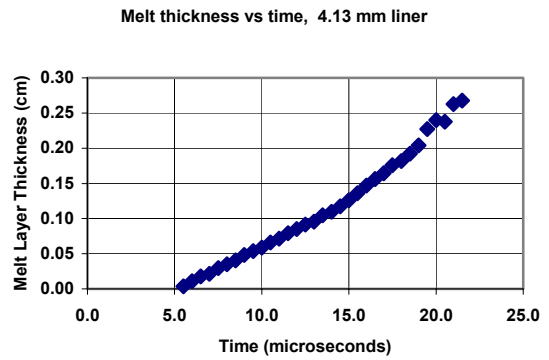
Melt thickness vs time, 4.13 mm liner

Fig. 8 Calculated thickness of liner that has zero mechanical strength (melt layer), for initially 4.13 mm thick, 5 cm outer radius liner driven by 1300 microfarad, 44 nanohenry, 160 KV discharge.